

# **Interaction of the Kuroshio with the East and the South China Seas and Nonlinear Wave Dynamics in the South China Sea**

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## **LONG TERM GOALS**

The long-term objective is to better understand the interactions between the Kuroshio and the China Seas with the coordinated use of several tools, some of which already developed by ONR: a numerical model, a Surface Velocity Program (SVP) drifters array and surface drifters that are configured to gather enhanced data. We intend to investigate the dynamical processes that govern this interaction. To achieve this goal, new observations are being obtained. A range of model parameters will be tested to find the combination that best represents the observed surface circulation. This research contributes to a more realistic prediction of this complex physical environment in area of strategic importance for PACFLEET operations.

## **OBJECTIVES**

The first objective is to obtain accurate velocity measurements at 15 m depth in the South China Sea and in the Luzon Strait region, in order to achieve more accurate Fall and Winter measurement of the existing current systems and of the upper ocean mass transport through the Luzon Strait. The second objective is to use the existing and new datasets of surface circulation to compare with the results of the ROMS numerical model to evaluate the model ability to reproduce a realistic flow field. A third objective is to utilize drifting platforms to make velocity and temperature profile observations of high amplitude, short period internal waves.

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## APPROACH

To accomplish the first objective, SVP drifters were assembled in Korea and were deployed from 2003 through 2006 in the Luzon Strait region during the inflow regime of the October-January period. In the 3<sup>rd</sup> year, the currents at 150 m were also measured with drifters. These measurements determine accurately the current systems of the SCS and aspects of the dynamics of the in-and-out flow through the Luzon Strait. To accomplish the second objective, various runs of the numerical model, made under an appropriate range of settings and forcings, are analyzed in terms of the East China Sea budget of mass, vorticity and thermal, potential and mechanical energies. The model set-up and the simulations are being performed by Prof. Lee and the drifter's data analysis is being performed by Dr. Luca Centurioni. They will both perform the interpretations of the drifter data and the comparison with the model outputs together with the principal investigator, Prof. Peter Niiler. Regarding the Internal waves experiment, Dr. Luca Centurioni and Prof. Peter Niiler have processed and started the interpretation of the data collected during the NLIWI '05 pilot experiment and NLIWI '07 main experiment with the overall goal of measuring the non-linear terms of the IW flow.

## WORK COMPLETED IN YF'07

### *Circulation studies in the South and East China Seas: observations*

Having completed the release of SVP drifters in the Luzon Strait, we have continued and finished the analysis of circulation and volume transport partially described in the FY06 report.

### *Circulation studies in the South and East China Seas: modeling*

Our numerical model (ROMS) was configured. It is forced by (1) mean sea level estimated from drifters (Niiler and Maximenko), (2) monthly 1/4 degree density from NOAA and (3) monthly mean wind from Quikscat. The inflow at the open boundary is nudged by monthly climate mean and the radiation condition at the open boundary is used for outflow.

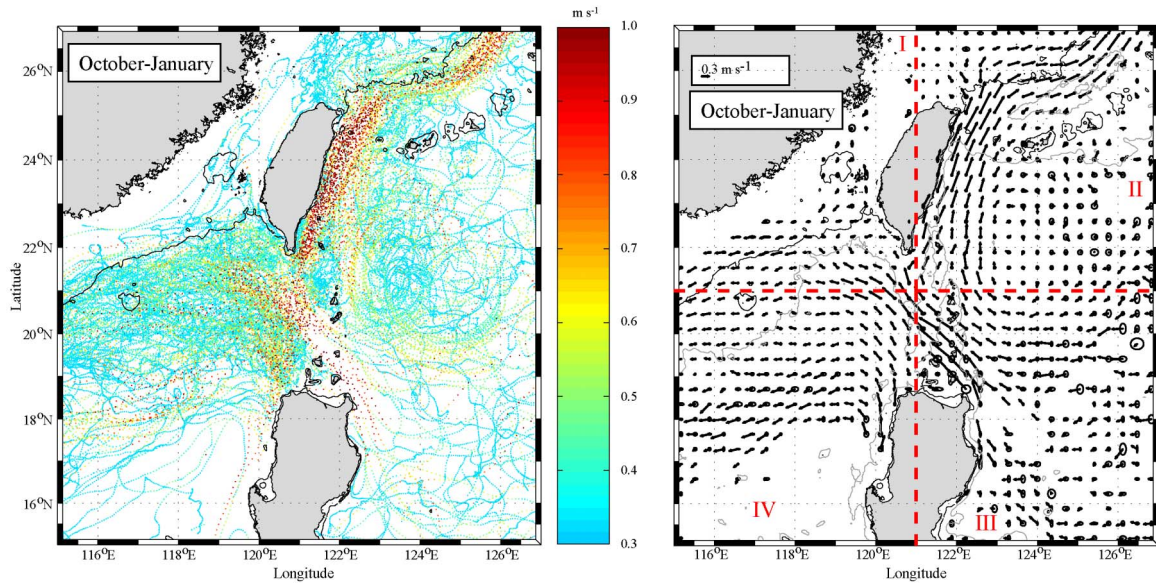
### *NLIWI*

For the NLIWI '07 experiment we successfully run two cruises at the end of April 2007 and beginning of May 2007 with the Taiwanese vessel *Ocean Researcher 2*, where Dr. Centurioni was the US PI. The cruises were preceded by the release of 10 SVP drifters (a contribution for the Global Drifter Program) to investigate the intensity of 15 depth currents in a range of possible deployment areas. The completed cruise program included the deployment and recovery of 8 drifting thermistor chains equipped with acoustic profiling current meters. CTD measurements, ship-board ADCP and echo-sounder measurements were also taken. As we write, the post-cruise calibration of the temperature and pressure sensors is underway. And the reduction/analysis of the data has begun.

## RESULTS

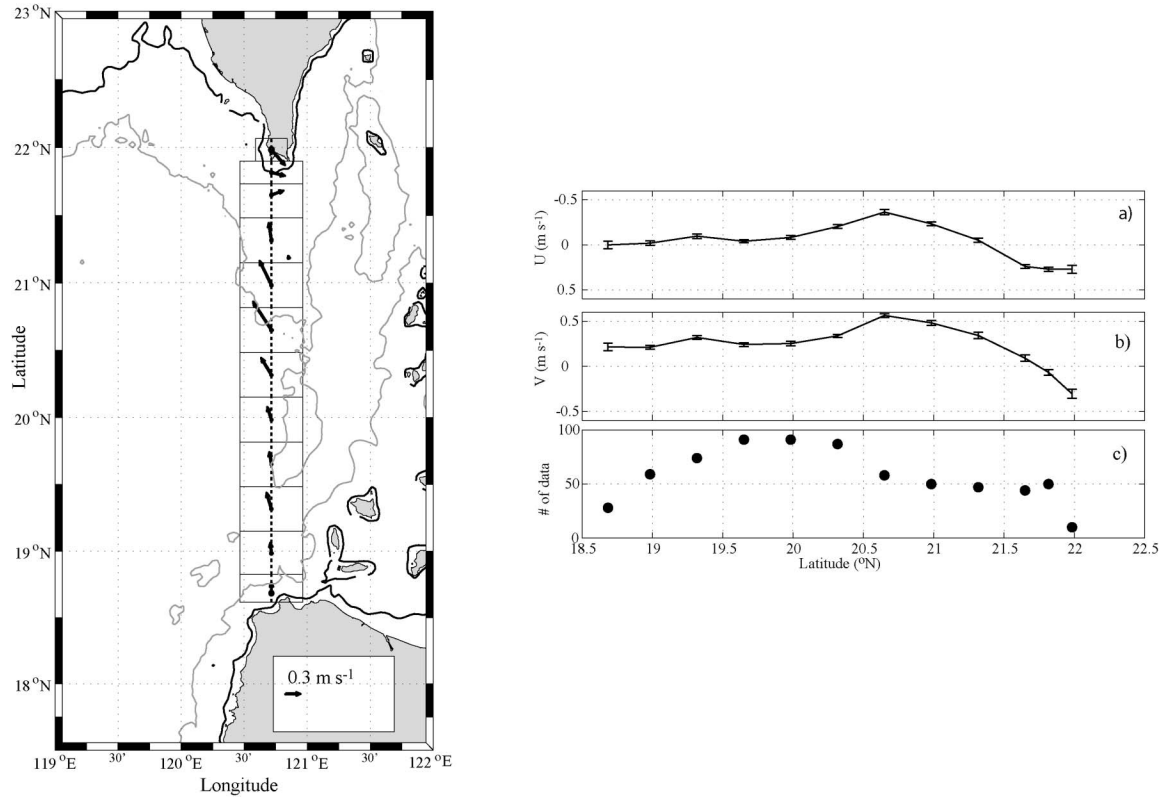
### *Surface currents and volume transport in the Luzon Strait*

Velocity measurements at 15 m depth obtained from the release of 259 Surface Velocity Program drifters between October 2003 and December 2005 near the Luzon strait were combined with the historical drifter data to measure the mean geostrophic circulation during the Winter Monsoon, between October and January (Figure 1).

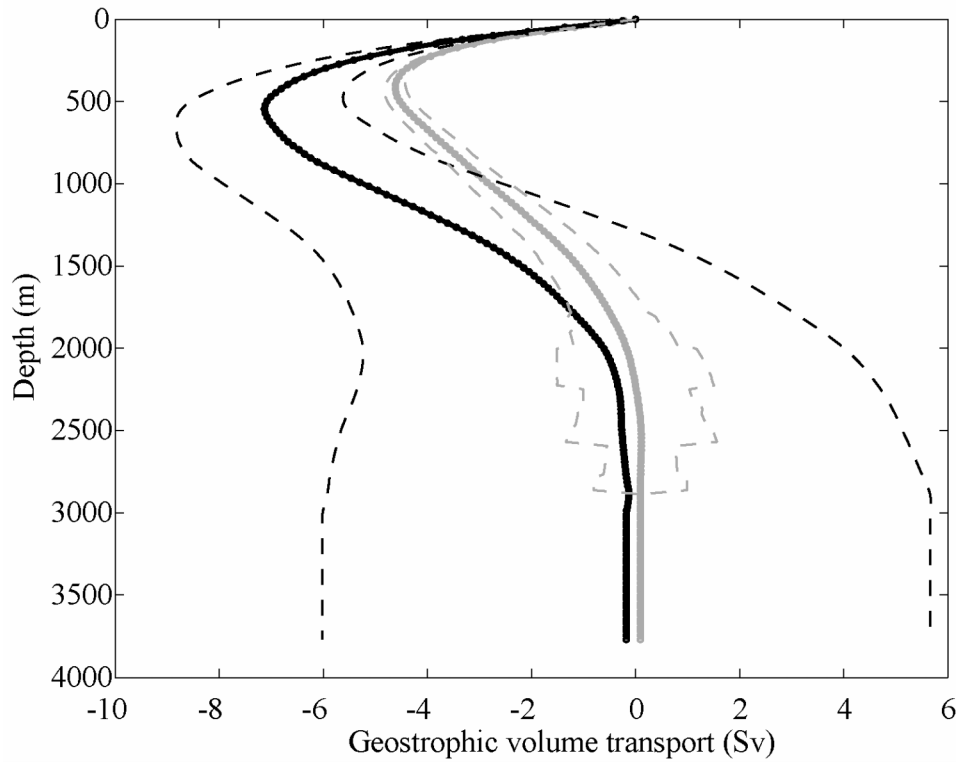


**Figure 1: Left: six hourly location of SVP drifting buoys (ONDJ) color coded in accordance with their instantaneous speeds. The time series were filtered with a 6 points (36 hours) wide running average filter. The 200 m bathymetry contours are shown. Right: mean total velocity ( $0.35^\circ \times 0.35^\circ$ , ONDJ) at 15 m depth computed from the dataset shown in a). Vectors computed from less than five pre-averaged observations are not shown. The dashed lines define the quadrants used for the computation of the Lagrangian statistics. The 200 m (black) and 2000 m (grey) bathymetry contours are shown.**

The data were then used to compute a reference zonal current to quantify the transport through the Luzon Strait and its uncertainty, from historical hydrographic data and along a transect running meridionally along the strait (Figures 2 and 3).



**Figure 2: Left: geostrophic velocity at 15 m depth computed from drifter data in the Luzon Strait along the transect located at  $120^{\circ} 43' \text{ E}$ . The 200 m (black) and 2000 m (grey) bathymetry contours are shown. Right: a) zonal component and standard error (50% confidence level) of the geostrophic velocity shown on the left, note that the y axis is reversed, with negative values upward; b) meridional component and standard error (50% confidence level) of the geostrophic velocity shown on the left; c) number of pre-averaged velocity data used to compute the mean velocities.**

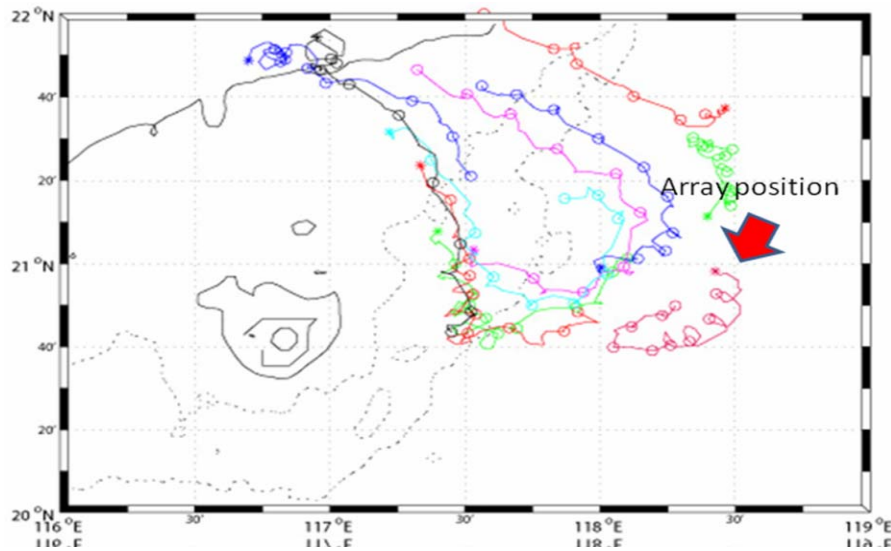


**Figure 3: The transport through the section integrated from the surface down as a function of depth based on the geostrophic velocity: referenced by drifters (black); referenced by vanishing velocity at the bottom (gray). The dashed lines indicate a 50% confidence interval. No hydrographic data are available below approximately 2900 m.**

The geostrophic volume transport has a maximum value of  $7.1 \pm 1.7$  Sv ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ) at 550 m depth. An additional 0.6 Sv is coming from the Ekman transport. The geostrophic volume transport referenced to the drifter velocity is 54% higher than the value obtained with the hypothesis of zero velocity near the bottom. Both computations of geostrophic volume transport agree on indicating that outflow from the SCS occurs below approximately 500 m depth and that its magnitude is sufficient for compensating the westward inflow

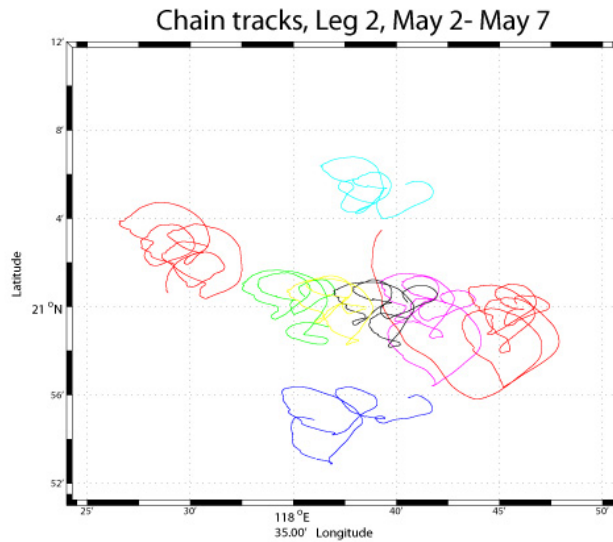
#### ***NLIWI***

The deployment of 10 SVP drifters was crucial to identify a location with minimal surface currents and dispersion where to deploy the drifting chains. Figure 4 shows the existence of much swifter currents at 15 m depth over the shallower part of the SCS north east of Dong-Sha atoll.



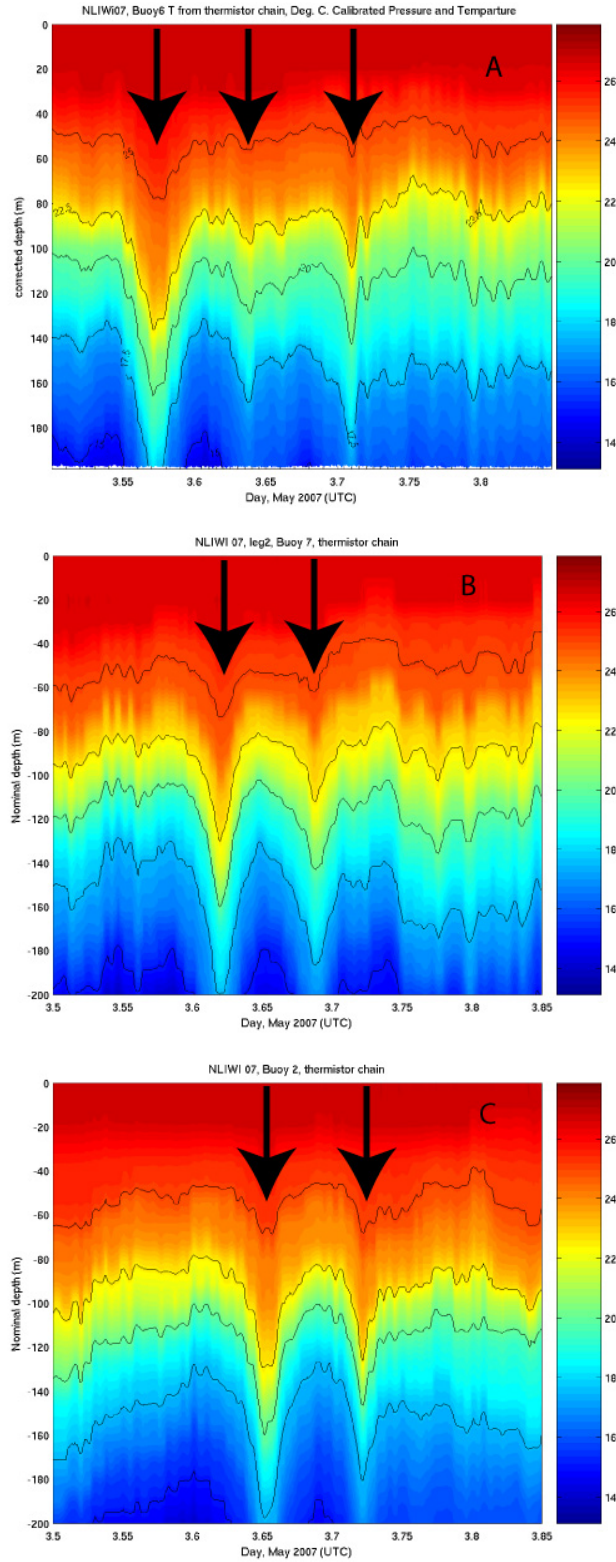
**Figure 4:** Tracks of 10 SVP drifters deployed before our OR2 cruise. The segment of track between two consecutive circles is 24 h long. The arrow indicates the location we choose to deploy our array of 8 drifting thermistor chains.

The close spacing of the array of drifting instrumented chains (Figure 5) and the fact that very little dispersion of the instruments occurred over the time of the experiment, allowed us to inspect the evolution of the internal waves.



**Figure 5:** track of the eight thermistor chains. Note that very little dispersion of the array occurred during the 6 days long leg of the cruise. Looping trajectories are caused by the tidal currents.

We indeed found that changes in the structure of the wave packet can occur over very short distances. A wave packet with three distinct depression waves (as indicated by the arrows in the figures) appears to be made of two after progressing for about 12 miles to the northwest (Figures 6A through 6C).

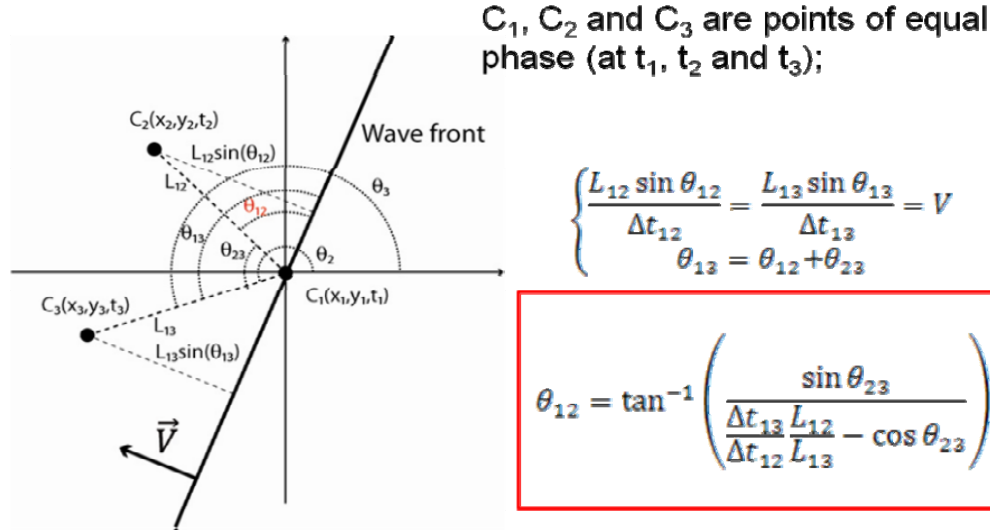


*Figure 6a-c: sequence of temperature contours from the same wave passing through three thermistor chains which are approximately six nautical miles apart along the direction of propagation of the waves.*



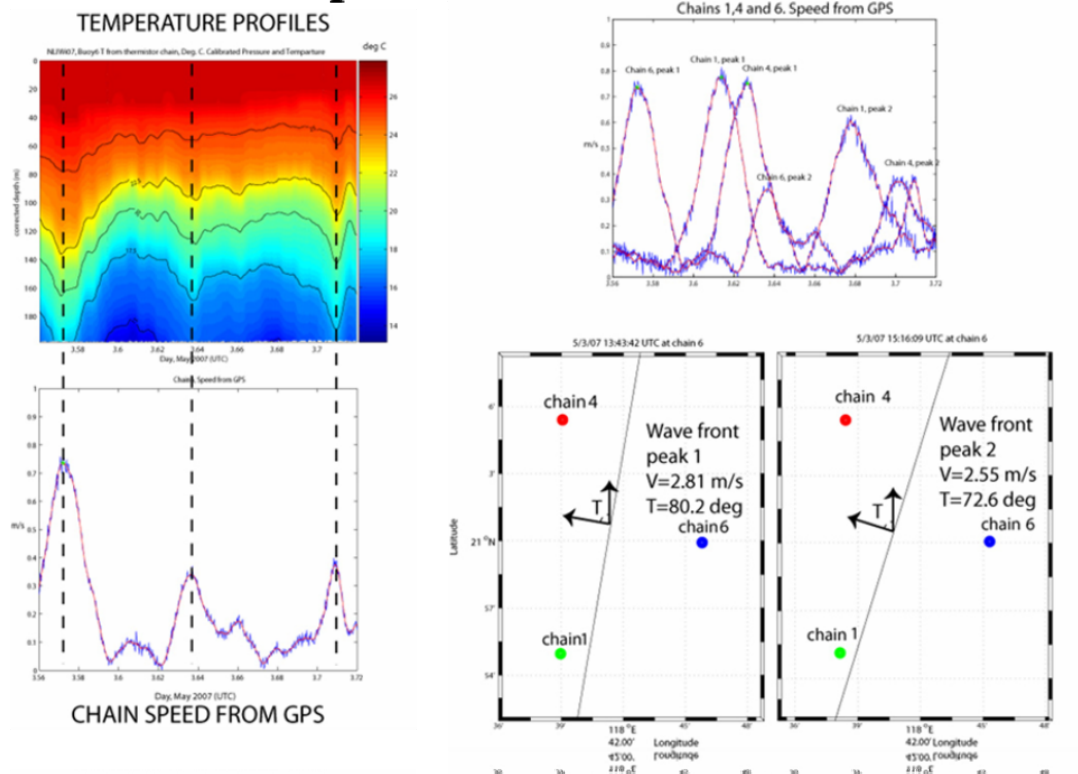
The accurate GPS positions of the drifting devices were exploited to use the array as an antenna. Points of equal phase of the waves were identified from vertical profiles of temperature and from the speed of the devices. Preliminary results suggest that the speed of the waves can be computed with great accuracy, which in turn means that we can compute the nonlinear terms of the flow. The phase speed computed for the leading wave of the packet observed on May 3, 2007 ranges between 2.75 to 2.81 m/s. Figures 7 and 8 summarize the procedure used to compute the phase speed of the waves.

## COMPUTATION OF WAVE SPEED AND DIRECTION



**Figure 7: Schematic showing the simple geometric construction used to compute the phase speed of the waves and the direction of the wave's front.**

# Waves speed and direction

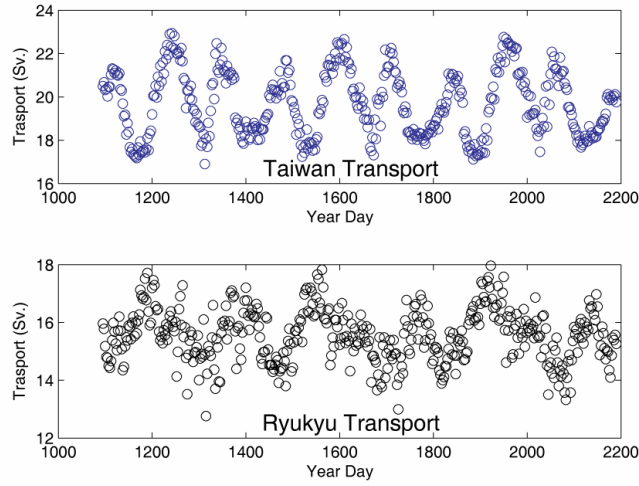


**Figure 8: example of computation of the phase velocity for the first two peaks of a wave packet observed in the South China Sea in May 2007. Three chains are used to form an antenna that detects times of equal phase of the wave at different locations (for example through a local maximum in the speed of the chain). Several combinations of three elements of our 8 units array can be used to obtain multiple measurement of the phase velocity of each wave packet.**

Our final result comes from the analysis of the CTD data collected during the two cruises. The speed of the one wave examined so far is nearly identical to the speed of the first mode baroclinic semidiurnal tide. Dr. Vitalii Sheremet is also working with the PI's on this topic.

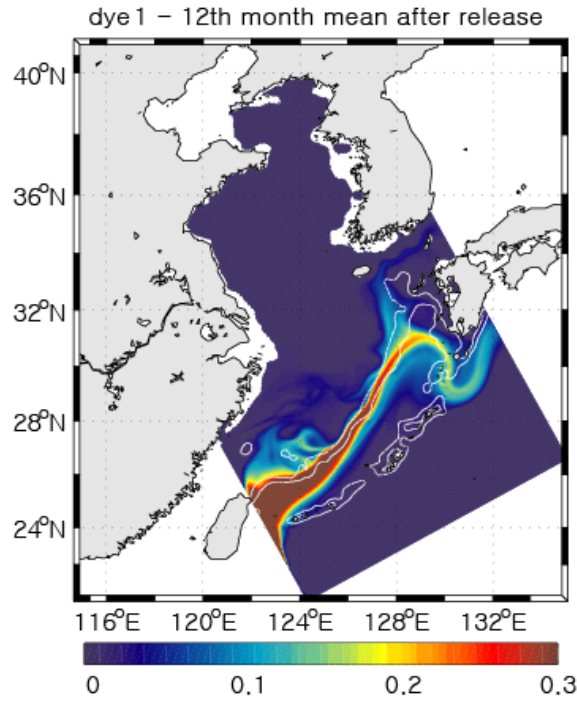
## Modeling

The mean transport of Kuroshio inflow near Taiwan is about 20 Sv. with 100 day period fluctuation (Figure 9). The fluctuations of the Ryukyu Current are out of pace with the Kuroshio inflow except summer seasons.



**Figure 9: Inflow Kuroshio transport near Taiwan and transport of Ryukyu Current.**

The tracer experiment in the Kuroshio inflow region shows major influx of Kuroshio water into the shelf in the region southwest of Kyusyu where Kuroshio leaves 150m depth contour and deflects eastward (Figure 10). The tracers intruded near Taiwan return to the Kuroshio and thus net mass flux between Kuroshio and the East China Sea in this region is very small.



**Figure 10: Tracer concentration in 12th month after continuous release of dye in the Kuroshio intrusion region**

## IMPACT/APPLICATIONS

The drifter data were placed on the GTS for use by global scientific community.

## TRANSITIONS

None

## RELATED PROJECTS

NOAA/OGP funded the “Global Drifter Program”

## PUBLICATIONS

Centurioni, L.R., P.P. Niiler and D.-K. Lee: Observations of inflow of the Philippine Sea surface water into the South China Sea through the Luzon Strait. *J. Phys. Oceanogr.* **34**, 113-121. (2004)

Centurioni L.R., P.P. Niiler, Y.Y. Kim, V.A. Sheremet and D.K. Lee: Near surface dispersion of particles in the South China Sea. In: Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics. A. Griffa, A. D. Kirwan, A. J. Mariano, T. Özgökmen, and T. Rossby Eds. Cambridge Univ. Press. (2007), 487 pp.

Centurioni L.R., V.A Sheremet, P.N. Niiler, D.K. Lee, Y.Y. Kim, M. Zhou, M. B. Shim, Circulation and Volume Transport in the Luzon Strait Region in Fall and Winter, Submitted to *J. Phys. Oceanogr.*

Pazan, S. E. and P.P. Niiler: New global drifter data set available. EOS, 85 (2), 17. (2004)

Niiler, P, W. Scuba and D.-K. Lee: The performance of Minimet wind drifters in hurricane *Fabian*. The Sea . *J. Korean Soc. Oceanography*, **9** (3), 130-136. (2004)

Ohlmann, J.C. and P.P. Niiler: Circulation over the continental shelf in the northern Gulf of Mexico. *Progress in Oceanography*, **64**, 45-81. (2005)

Ohlmann, J. C., P.F. White, A. L. Sybrandy, and P. P. Niiler: 2005: GPS-Cellular drifter technology for coastal ocean observing systems *J.A.O. Tech.* 22 (9) 1381

T. Bengtsson, R. Milliff, R. Jones, D. Nychka and P.P. Niiler: "A State-space model of ocean drifter motions dominated by inertial oscillations", *J. Geophys. Res.*, 110 (C10): Art. No. C10015

Lee, D.-K. and P.P. Niiler: The energetic surface circulation patterns of the Japan/East Sea. (In Press *Deep-Sea Research II*)

Lordbacher, K., d. Dommenges, P.P. Niiler and A. Kohl: Ocean mixed layer depth: A subsurface proxy of ocean-atmosphere variability , *J. Geophys. Res.*, In Press.

Niiler P.P. and N. Maximenko: Surface current observations. In State of the Climate in 2004: BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY 86 (6): S1. (D.H. Levinson Ed)